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Mars 2020 Mobility Actuator Thermal Testing and Model Correlation

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Introduction

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- An operability trade study was initiated in April 2014 to look at ways to improve the operability of the M2020 Rover.
  - On MSL, actuator thermal models used bearing conductance for a vacuum and neglected gear-to-gear contact in actuators.
  - This approach was conservative, and appropriate, but resulted in long warm up times, reducing the operability of the rover.

- Mobility actuators present lots of opportunity for productivity improvement through energy and time savings:
  - 10 Actuators
  - ~ 55 Kg Heated Mass
  - Gets used almost daily

- Areas of improvement for thermal were identified:
  - **Perform thermal testing on WSA-2 life test actuator** (**Accepted**)
  - Use more heater tables, or new heater algorithm (**Accepted**)
  - Add additional heater power to the WSAs (Rejected)
  - Requalify WSAs to -90 °C (Rejected)

Test Objective

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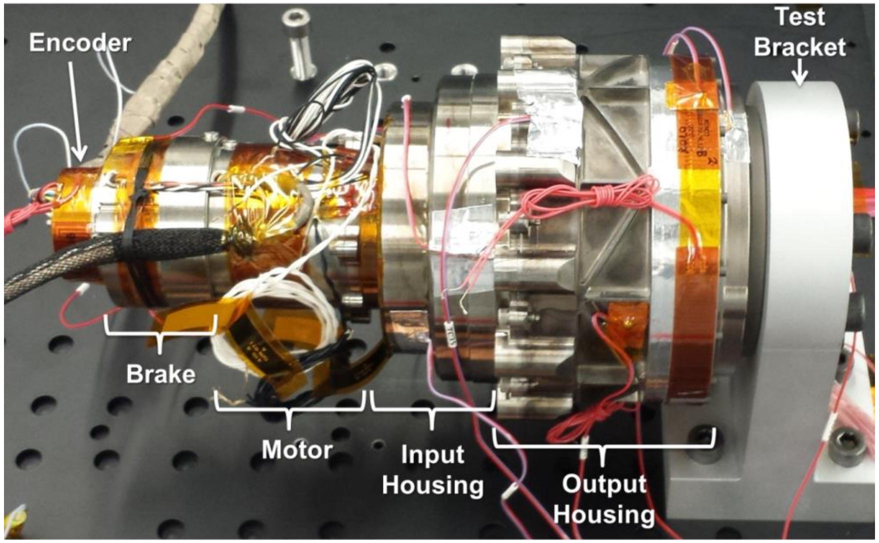
Primary Objective (Requirement): Gather steady state and transient test data the actuator internal components which will allow the thermal team to correlate a thermal model of the actuator, making the warm up predictions more accurate and less conservative.

Secondary Objective (Goal): Gain a better understanding of how heat is transferred across lubricated ball bearings and gear-to-gear contact in planetary gear trains.

Test Overview

- Thermal testing took place in May 2016 at JPL.

- Testing Consisted Of :
  - 3 Broad Test Categories:
    - Vacuum Testing
    - N_2 Testing, 6 torr
    - CO_2 Testing, 6 torr
  - 3 Heater Configurations:
    - Output Only
    - Input Only
    - Combined



WSA-2 Life Test Actuator and Support Bracket

Bearing Review & Test Conservatism

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- Larger bearings have higher thermal conductance

- Bearing load weakly affects lubricated bearing conductance
  - *Application: Test with a lightly loaded actuator*

- The presence of gas is expected to significantly increase bearing conductance by a factor of 3 to 10.
  - *Application: Test at lower bound Mars pressure (6 torr instead of 10 torr)*

- Lubricated bearings can have conductance which is a function of temperature
  - Likely due to temperature dependent properties of lubricant
  - *Application: Test at a lower range of temperatures*

- Bearing lubrication and run-in can strongly affect conductance
  - The longer a bearing is run, the more lubricant it loses, reducing its conductance.
    - *Application: Life test actuator was used, which has already been run significantly*
  - Resting a bearing for an extended period of time (weeks - months) can cause lubricant migration, and increase the conductance of a bearing.
    - *Application: Actuator was operated for 2 hours prior to instrumenting*

Test Article Overview

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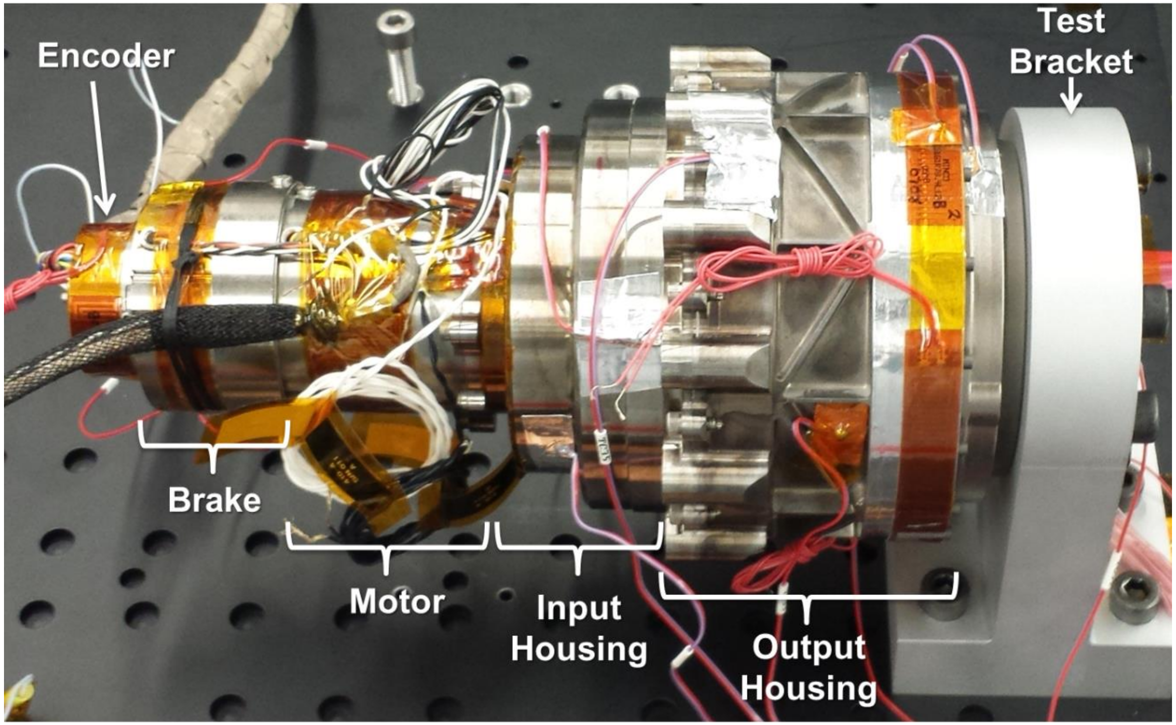
- WSA-2 life test actuator (WSA-2; Aeroflex P/N 16376-1 S/N 008)
  - Used on MSL for life testing: Wet lubricated components were tested to 2x life. The motor pinon gear was then re-lubricated. Additional 1x life testing (for total of 3x) was then performed to qualify the dry lubricated rotor.



WSA-2 Life Test Actuator and Support Bracket

Test Article Cross Section

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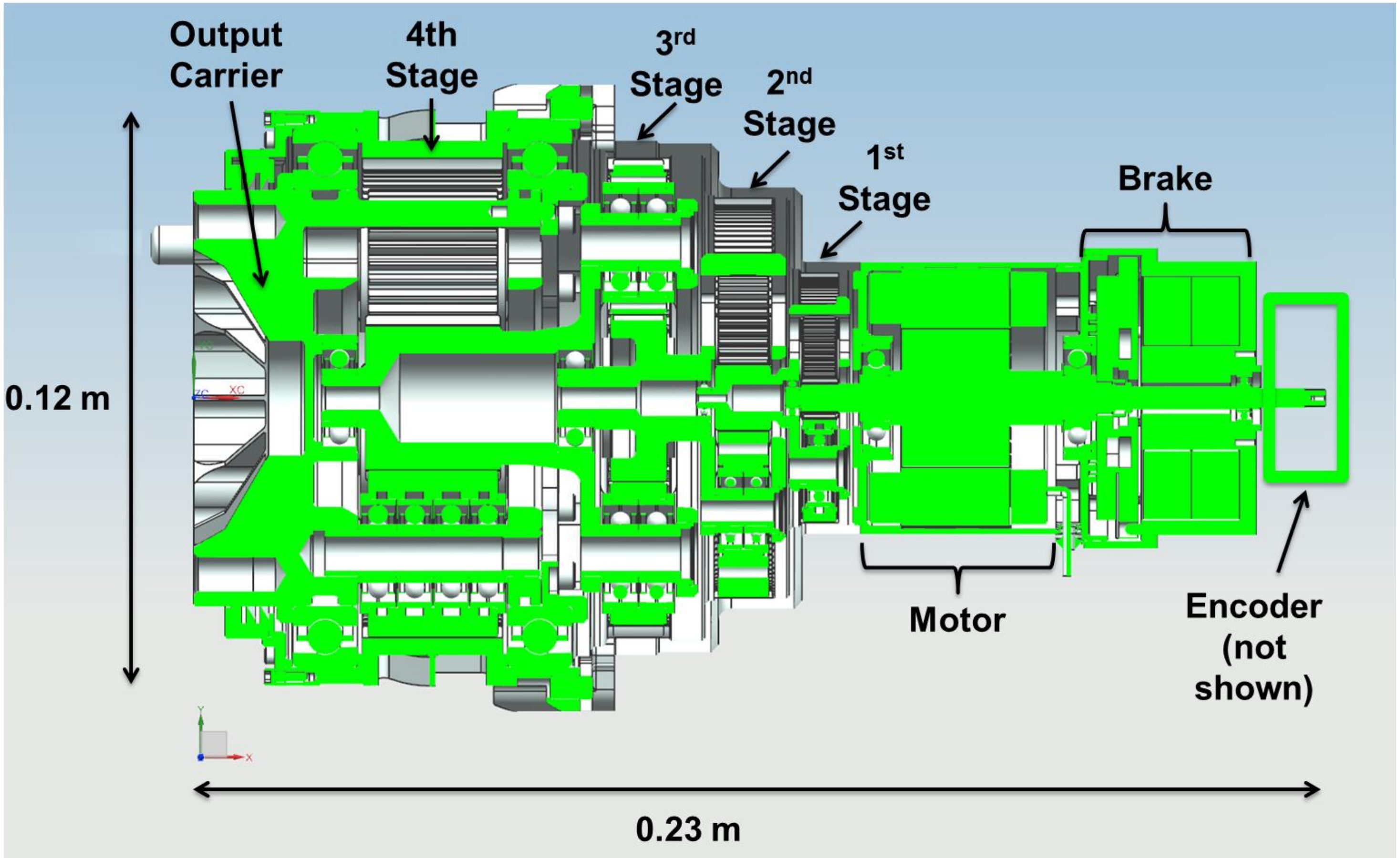
- WSA-2 Cross Section
  - 4 Stage Planetary gear train



Test Article Materials and Coatings

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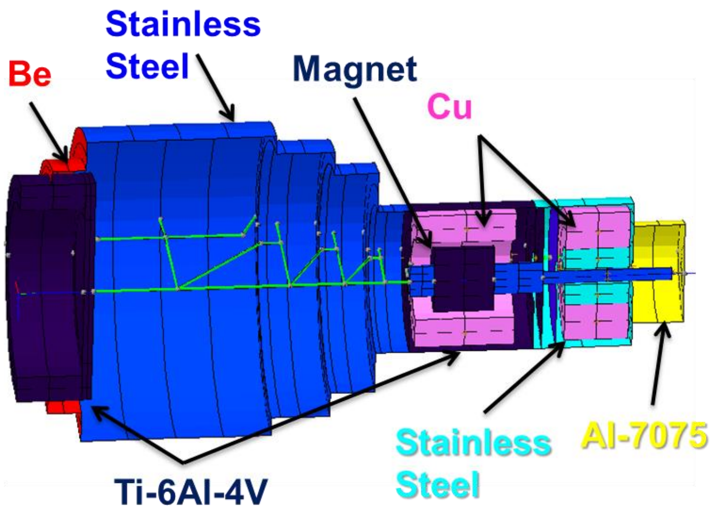
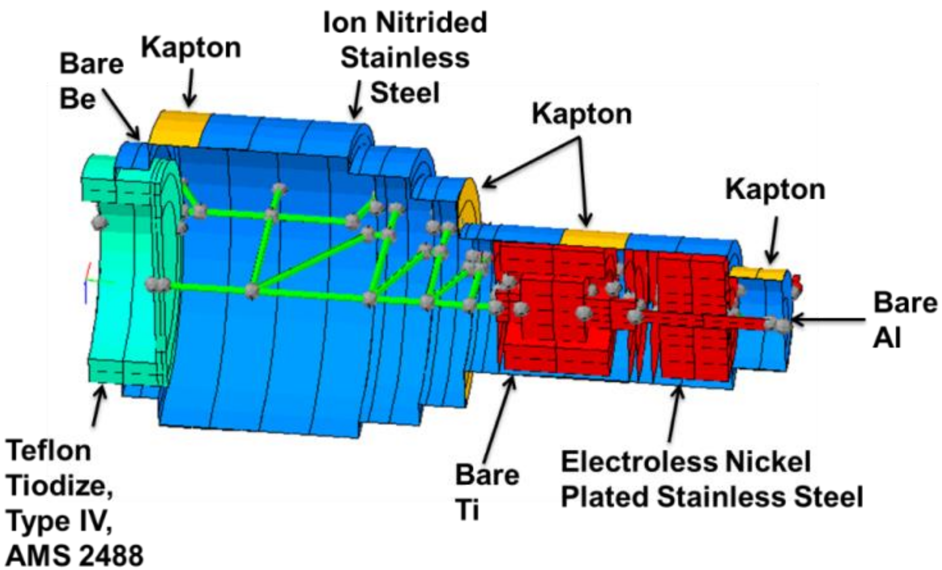
- Materials and Surface Coatings used in WSA-2
  - As represented in Thermal Model



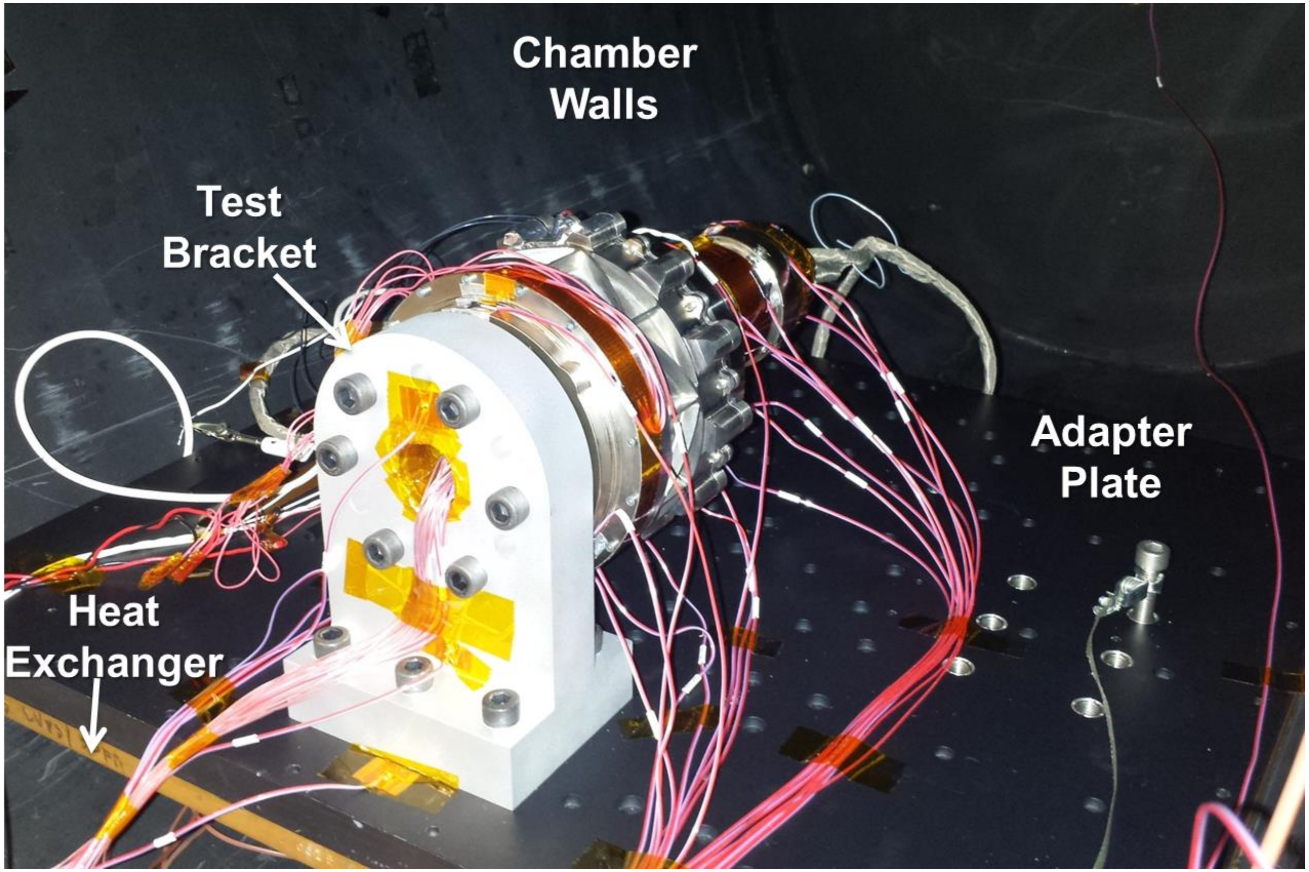
Materials



Surface Coatings

Test Setup

- WSA-2 was mounted to an Al-6061 Test Bracket, which was mounted to a Mg Adapter Plate, and a Cu Heat Exchanger

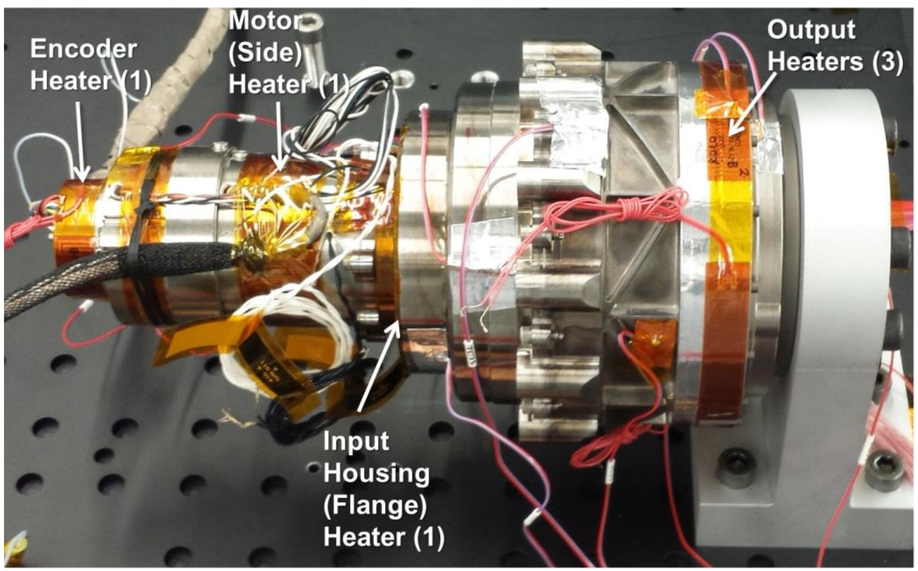


Test configuration with test bracket, adapter plate, heat exchanger, and 3 foot chamber

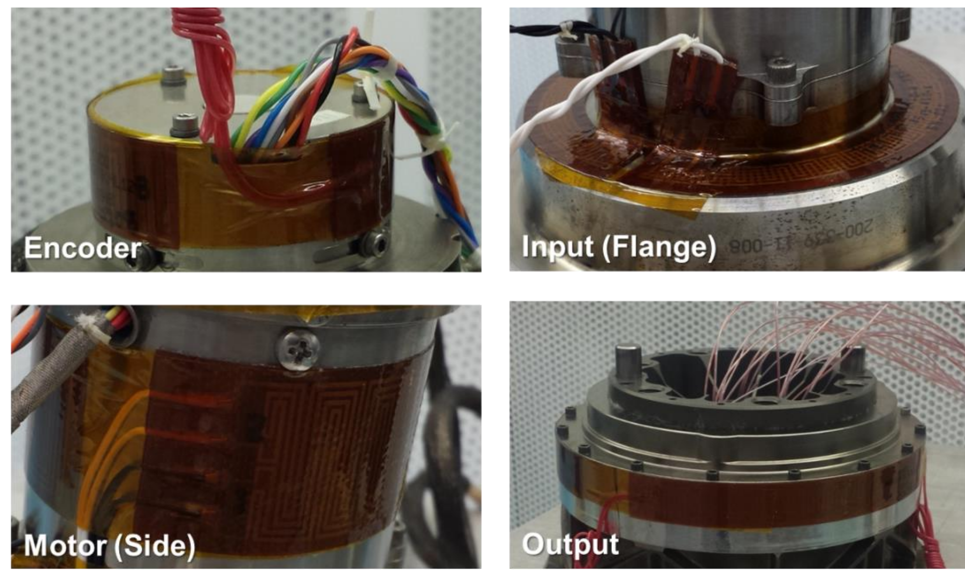
Heater Locations

- A total of 6 heaters were applied to 4 locations:

Heater Location	Number of Heaters	Heater Resistance (Ω)	Dimensions
Output*	3	78	4” x 0.5” (each)
Input Housing (Flange)	1	53.3	3.19” OD, 1.52” ID
Motor (Side)	1	106.7	0.94” x 6.49”
Encoder	1	83	4” x 0.5”



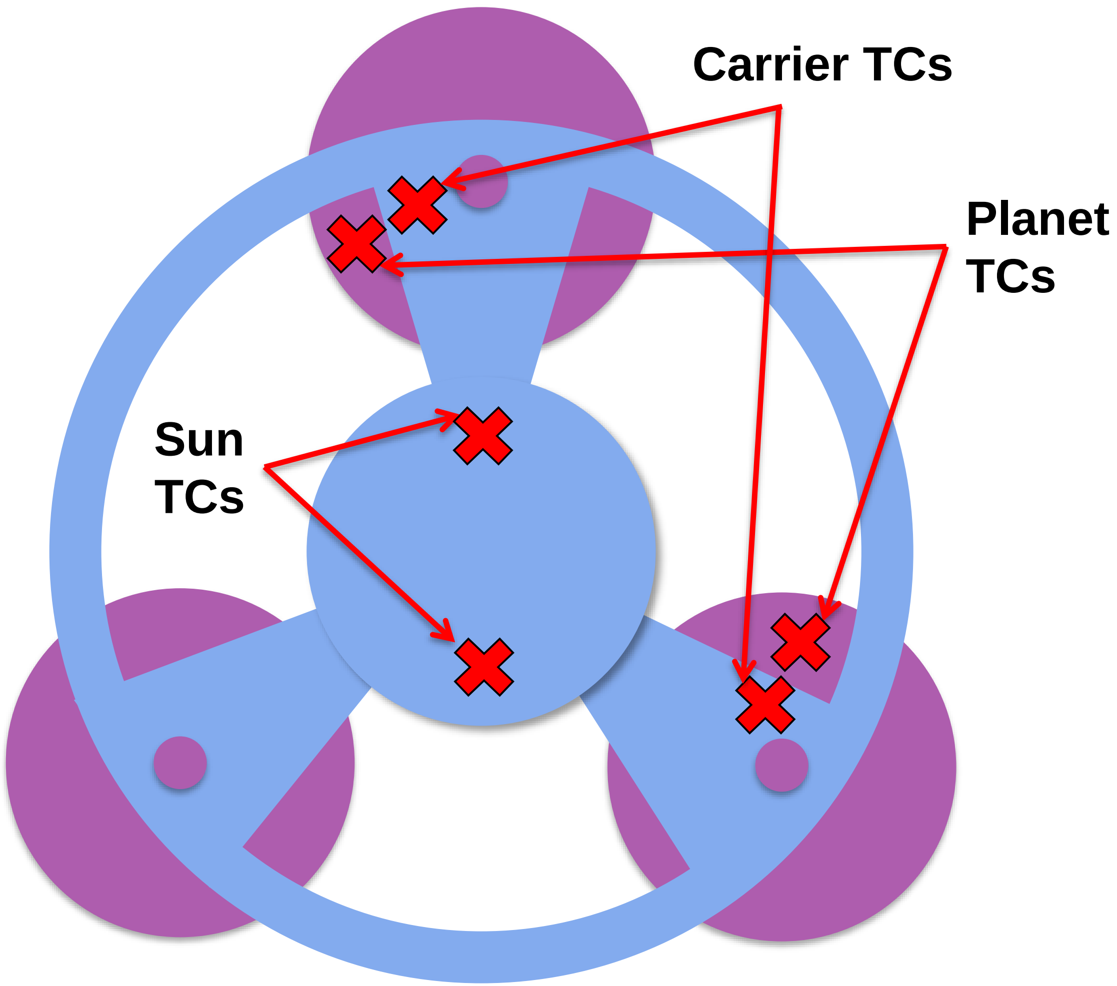
Heater Locations



Close Up of Heater Locations

Thermocouple Locations

- Each Stage has 2 Planet TCs, 2 Sun Gear TCs, and 2 Carrier TCs.
- Top and Bottom TCs used to asses gravity influence.



Actuator Thermocouple Locations

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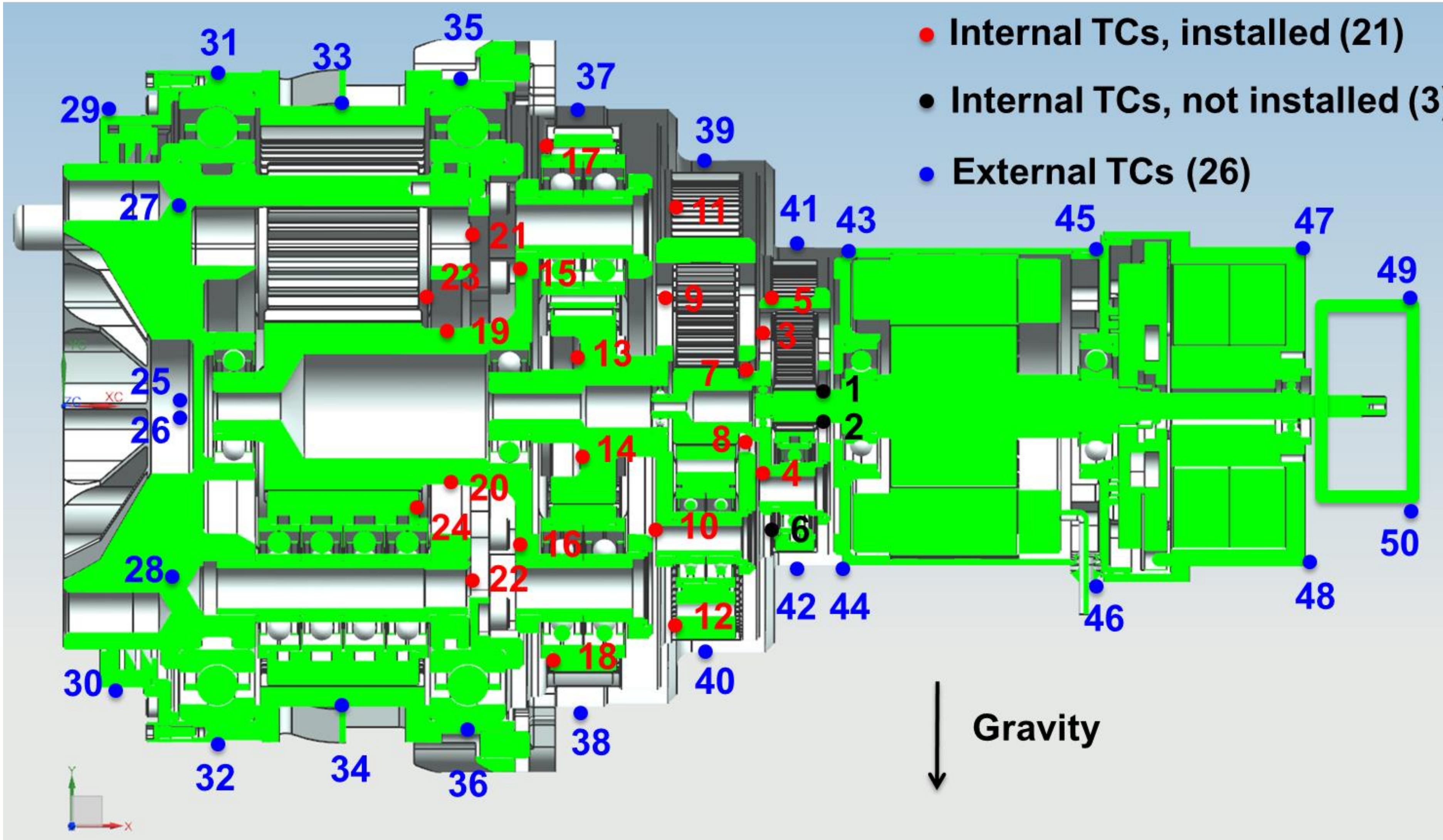
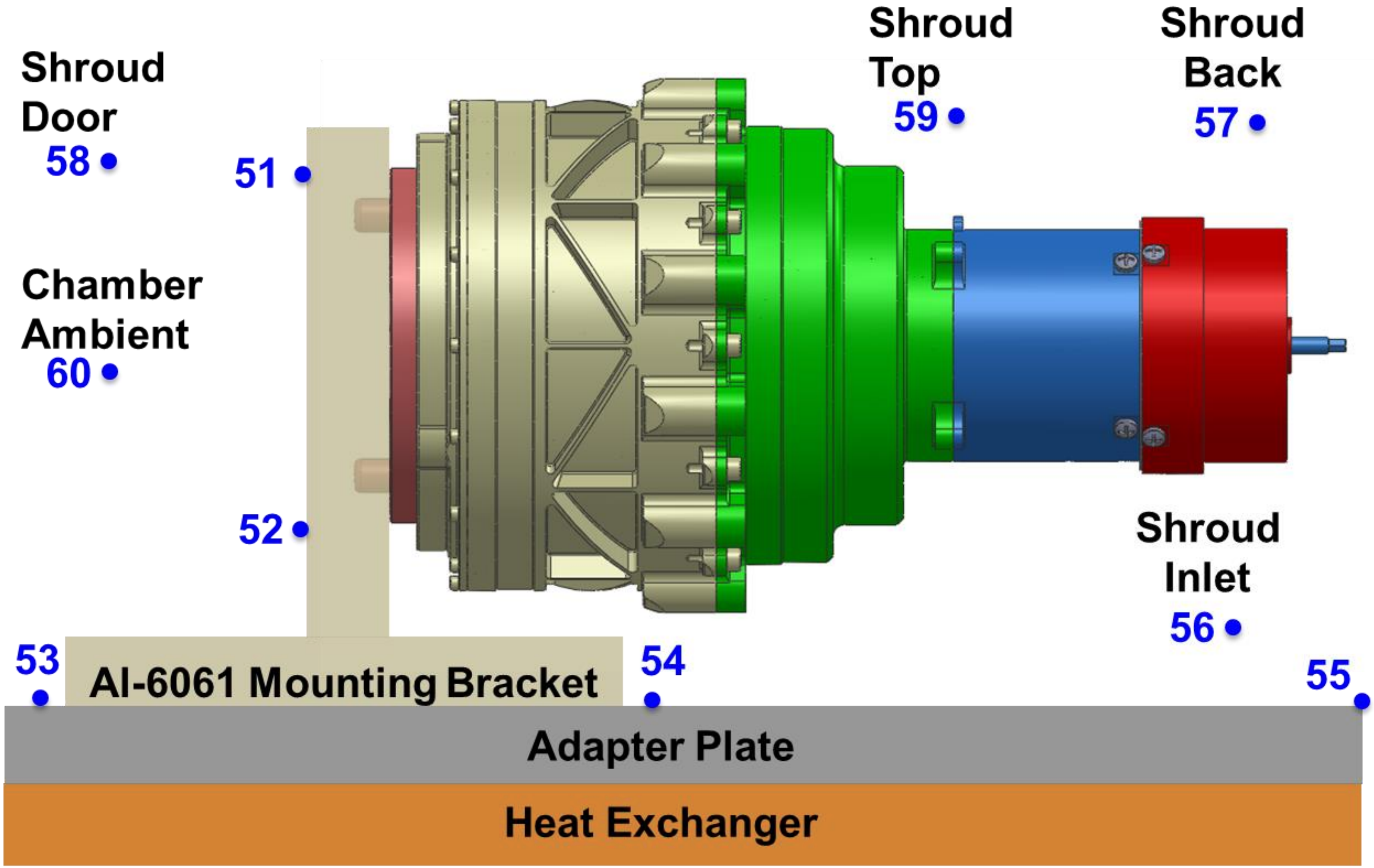
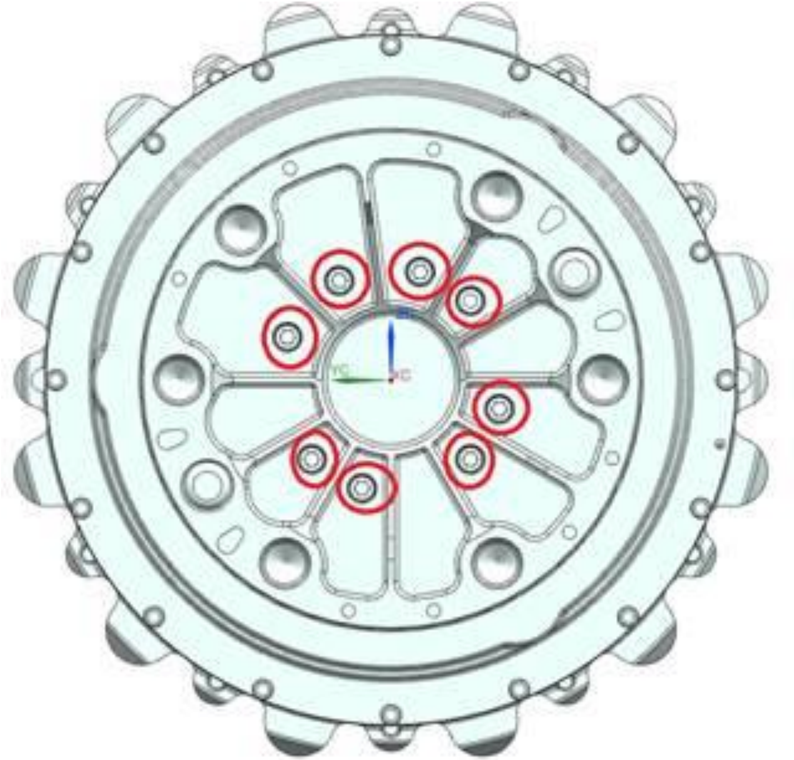


GSE Thermocouple Locations

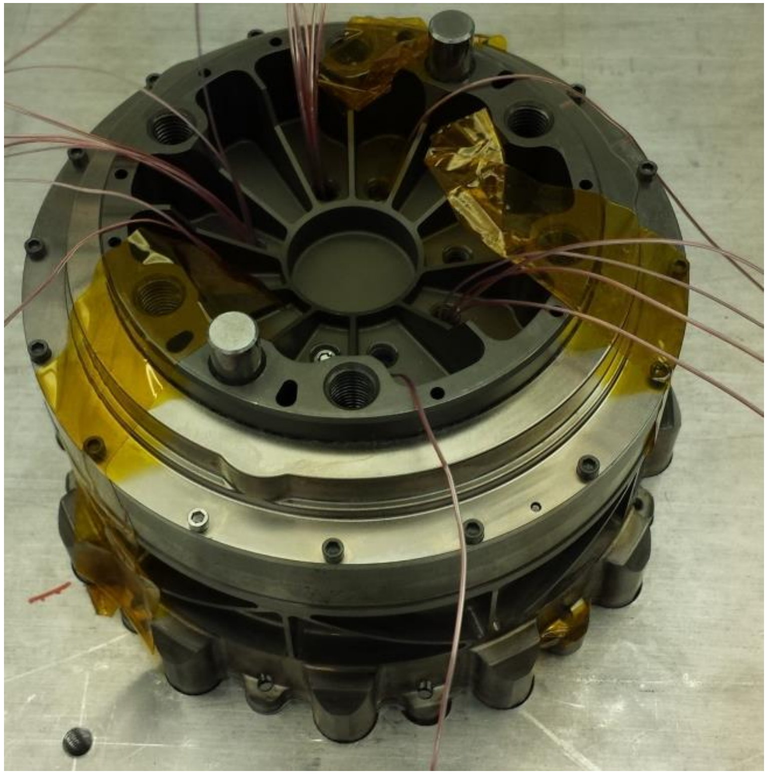


Vent Holes for TC Access

- TC leads were routed from the interior to exterior of the actuator through vent holes in the actuator output.



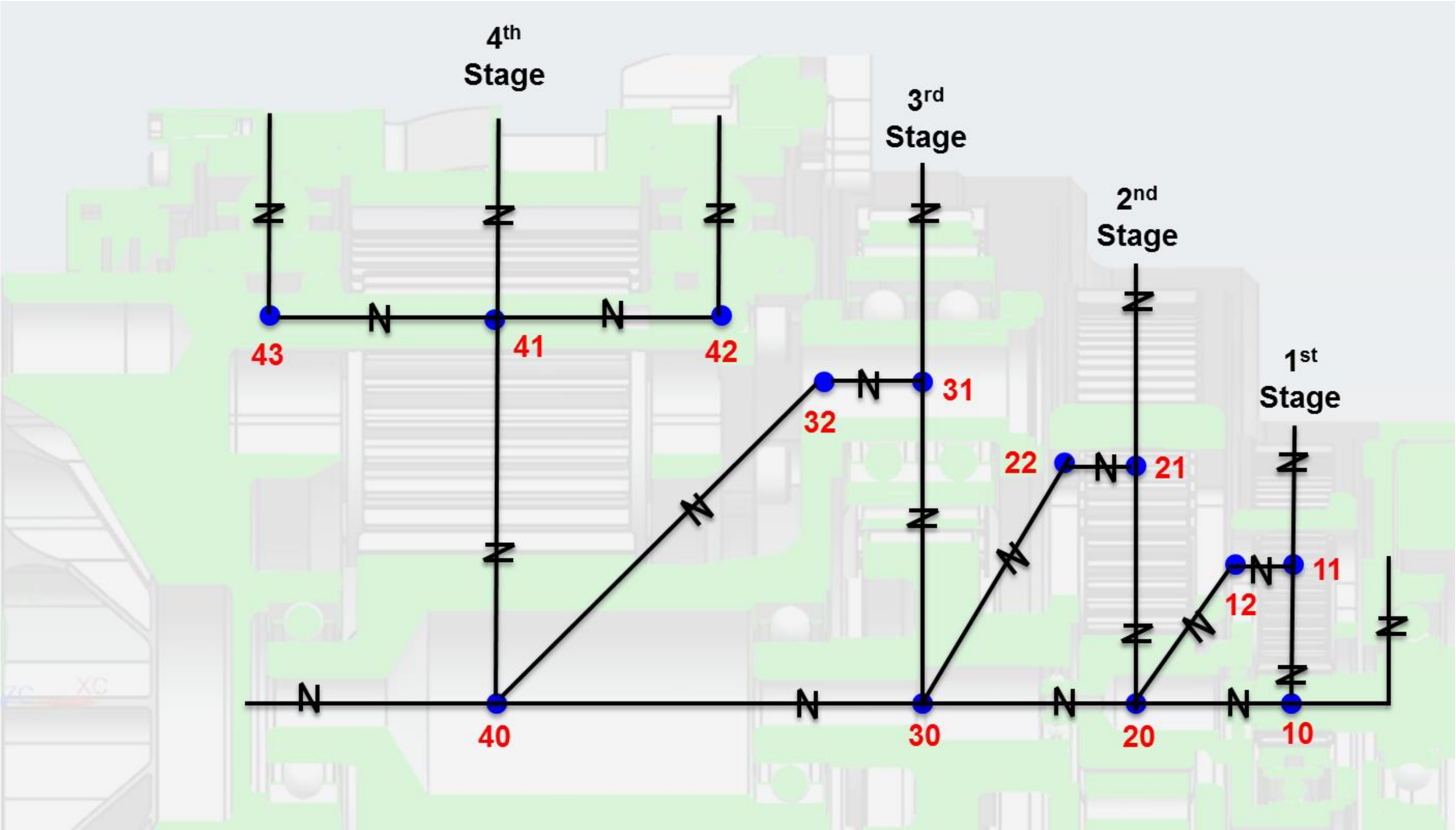
Vent Hole Schematic



TCs exiting through Vent Holes

Simplified Thermal Model

- Simplified thermal model nodes match TC locations to aid in thermal model correlation.



As Run Test Matrix

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Test Number	Description	Pressure	Atmosphere	Shroud Temperature	Heat Exchanger Temperature	Output Power	Input Flange Power	Input Motor Power	Encoder Power	Total Power
		(Torr)		(C)	(C)	(W)	(W)	(W)	(W)	(W)
1.0	Pump Down	760 torr to 1e-5 torr	Air	Floating	Floating	0.0	0.0	0.0	0.0	0.0
1.1	Cool Down, Vacuum	< 1.0 e -5	Vacuum	-100	-100	0.0	0.0	0.0	0.0	0.0
1.2	Output Heater Warm Up, Vacuum	< 1.0 e -5	Vacuum	-100	-100	**22.0**	0.0	0.0	0.0	**22.0**
1.3	Cool Down, Vacuum	< 1.0 e -5	Vacuum	-100	-100	0.0	0.0	0.0	0.0	0.0
1.4	Input Heater Warm Up, Vacuum	< 1.0 e -5	Vacuum	-100	-100	0.0	**6.6**	**3.2**	**3.2**	**13.0**
1.5	Cool Down, Vacuum	< 1.0 e -5	Vacuum	-100	-100	0.0	0.0	0.0	0.0	0.0
1.6	Combined Heater Warm Up, Vacuum	< 1.0 e -5	Vacuum	-100	-100	**11.0**	**3.3**	**1.6**	**1.6**	**17.5**
1.7	Cool Down, Vacuum	< 1.0 e -5	Vacuum	-100	-100	0.0	0.0	0.0	0.0	0.0
2.0	Vacuum to N_2 Transition	6 +/- 1	N_2	-100	-100	0.0	0.0	0.0	0.0	0.0
2.1	Output Heater Warm Up, N_2	6 +/- 1	N_2	-100	-100	**22.0**	0.0	0.0	0.0	**22.0**
2.2	Cool Down, N_2	6 +/- 1	N_2	-100	-100	0.0	0.0	0.0	0.0	0.0
2.3	Input Heater Warm Up, N_2	6 +/- 1	N_2	-100	-100	0.0	**6.6**	**3.2**	**3.2**	**13.0**
2.4	Cool Down, N_2	6 +/- 1	N_2	-100	-100	0.0	0.0	0.0	0.0	0.0
2.5	Combined Heater Warm Up, N_2	6 +/- 1	N_2	-100	-100	**11.0**	**3.3**	**1.6**	**1.6**	**17.5**
3.0	Heat Exchanger and Shroud Transition, N_2	6 +/- 1	N_2	-20	-20	0.0	0.0	0.0	0.0	0.0
3.1	Soak to Steady State, N_2	6 +/- 1	N_2	-20	-20	0.0	0.0	0.0	0.0	0.0
3.2	Input Heater Warm Up, N_2	6 +/- 1	N_2	-20	-20	0.0	**3.3**	**1.6**	**1.6**	**6.5**
3.3	Cool Down, N_2	6 +/- 1	N_2	-20	-20	0.0	0.0	0.0	0.0	0.0
3.4	Transition to CO_2	6 +/- 1	CO_2	-20	-20	0.0	0.0	0.0	0.0	0.0
3.5	Input Heater Warm Up, CO_2	6 +/- 1	CO_2	-20	-20	0.0	**3.3**	**1.6**	**1.6**	**6.5**
3.6	Cool Down, CO_2	6 +/- 1	CO_2	-20	-20	0.0	0.0	0.0	0.0	0.0
4.0	Return to Ambient	6 +/- 1	CO_2	30	30	0.0	0.0	0.0	0.0	0.0
4.1	Chamber Break	6 +/- 1	CO_2	30	30	0.0	0.0	0.0	0.0	0.0

Post Test Inspection & Disassembly

- During actuator disassembly process, a wrench was used to break an adhesive bonded interface, and the output half of the actuator was violently rotated ~30°.
- During inspection, it was observed that a number of TCs had debonded.
  - It is unknown whether the TCs debonded during the test or disassembly.
- **It is likely that TCs debonded during disassembly:**
  - Several actuator locations had one TC remain bonded, and one TC debonded.
  - Several actuator locations had both TCs debond
  - These TCs were all within 2 °C of one another during the test.
  - **If these TCs debonded during the test, large ΔTs would have been expected.**

Description	Top TC		Bottom TC	
	TC Number	Status	TC Number	Status
1st Stage Sun	1	**Not Installed**	2	**Not Installed**
1st Stage Carrier	3	**Debonded**	4	**Did Not Debond**
1st Stage Planet	5	**Debonded**	6	**Not Installed**
2nd Stage Sun	7	**Debonded**	8	**Did Not Debond**
2nd Stage Carrier	9	**Debonded**	10	**Debonded**
2nd Stage Planet	11	**Debonded**	12	**Debonded**
3rd Stage Sun	13	**Did Not Debond**	14	**Debonded**
3rd Stage Carrier	15	**Did Not Debond**	16	**Did Not Debond**
3rd Stage Planet	17	**Did Not Debond**	18	**Did Not Debond**
4th Stage Sun	19	**Debonded**	20	**Debonded**
4th Stage Carrier	21	**Did Not Debond**	22	**Did Not Debond**
4th Stage Planet	23	**Debonded**	24	**Debonded**

Chamber Pressure

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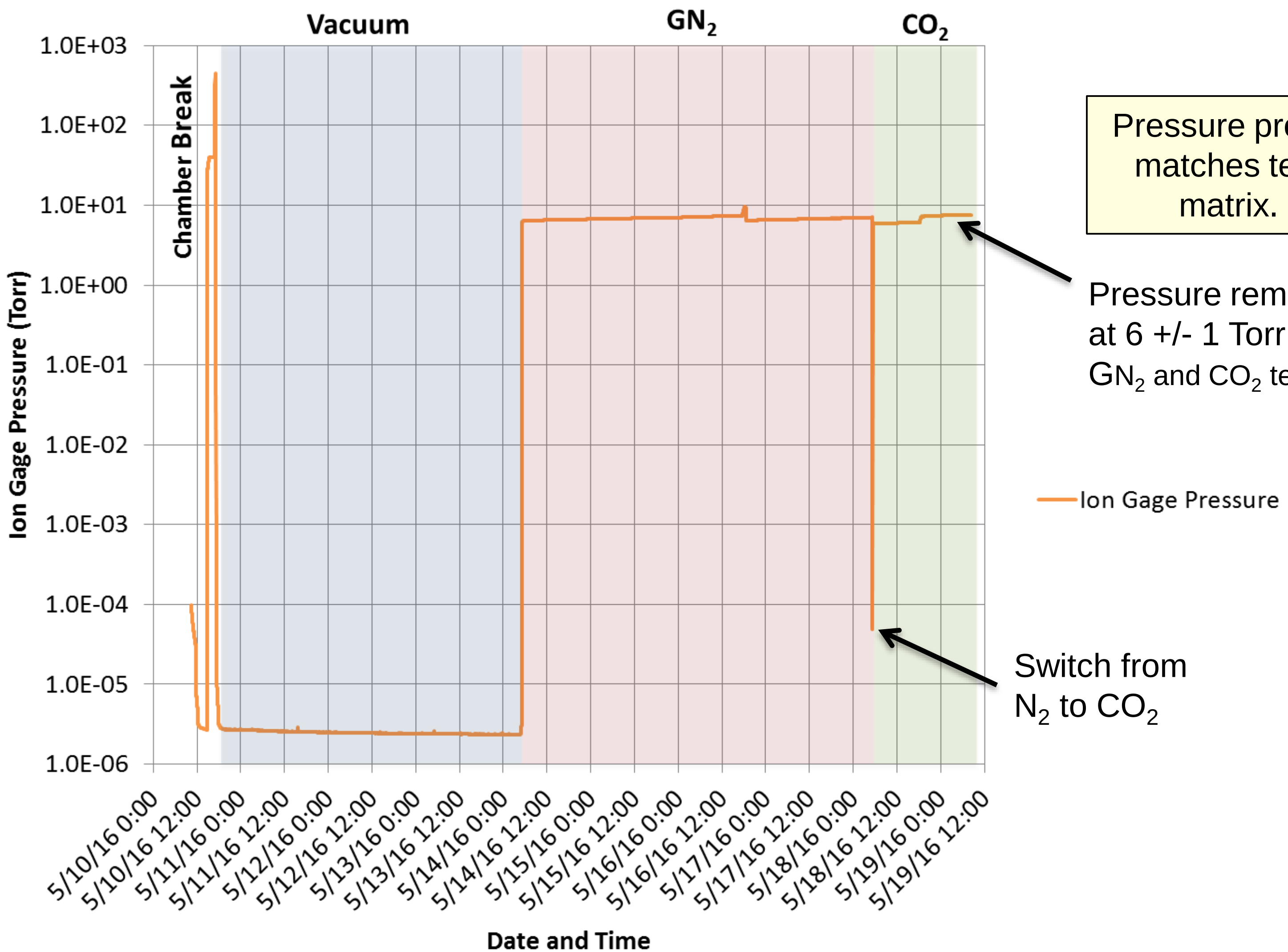

Pressure profile matches test matrix.

Pressure remained at 6 +/- 1 Torr for GN_2 and CO_2 testing

Switch from N_2 to CO_2

Heater Power

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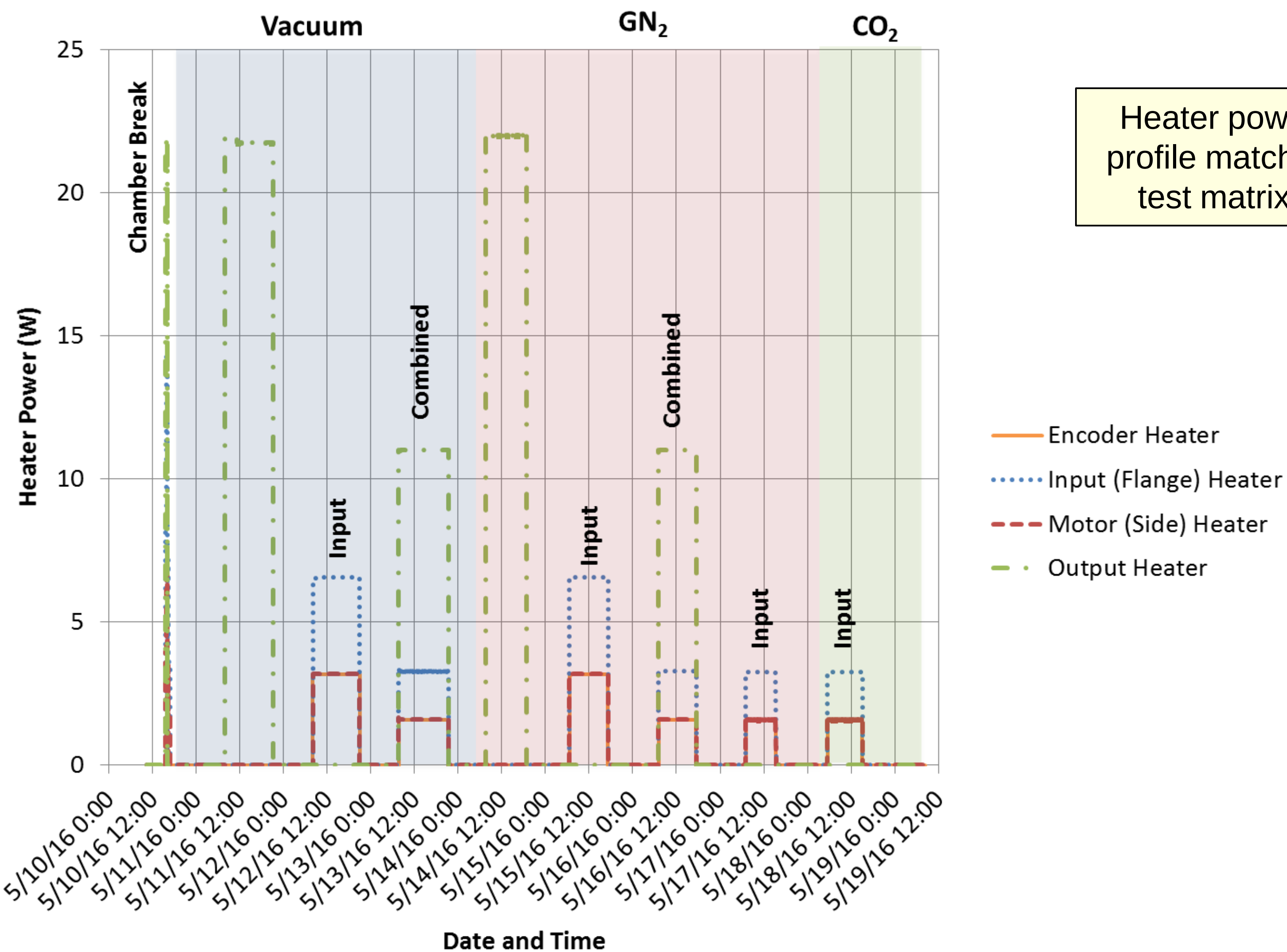

Heater power profile matches test matrix.

GSE Temperatures

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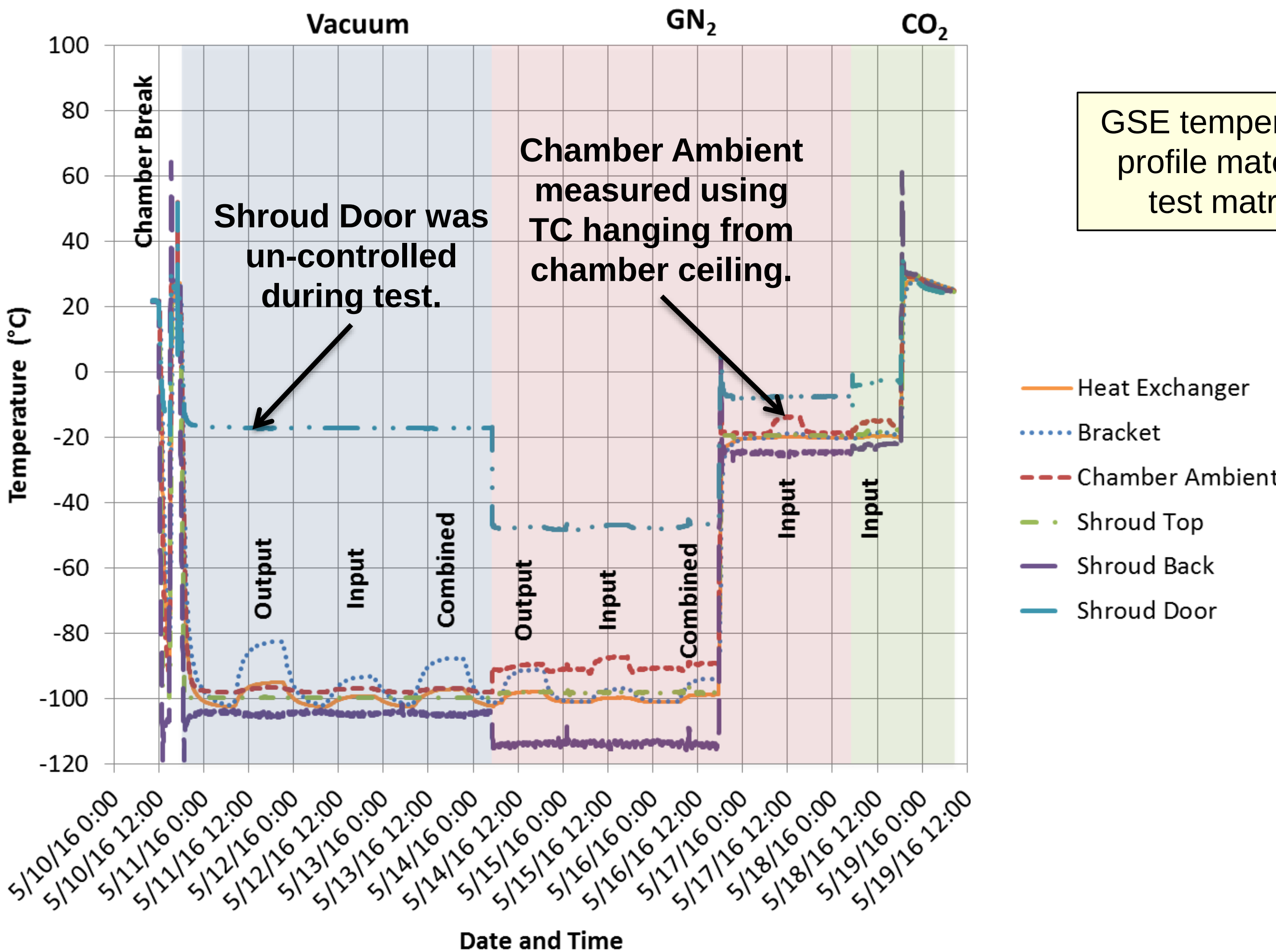

GSE temperature profile matches test matrix.

Redundant TC Comparison

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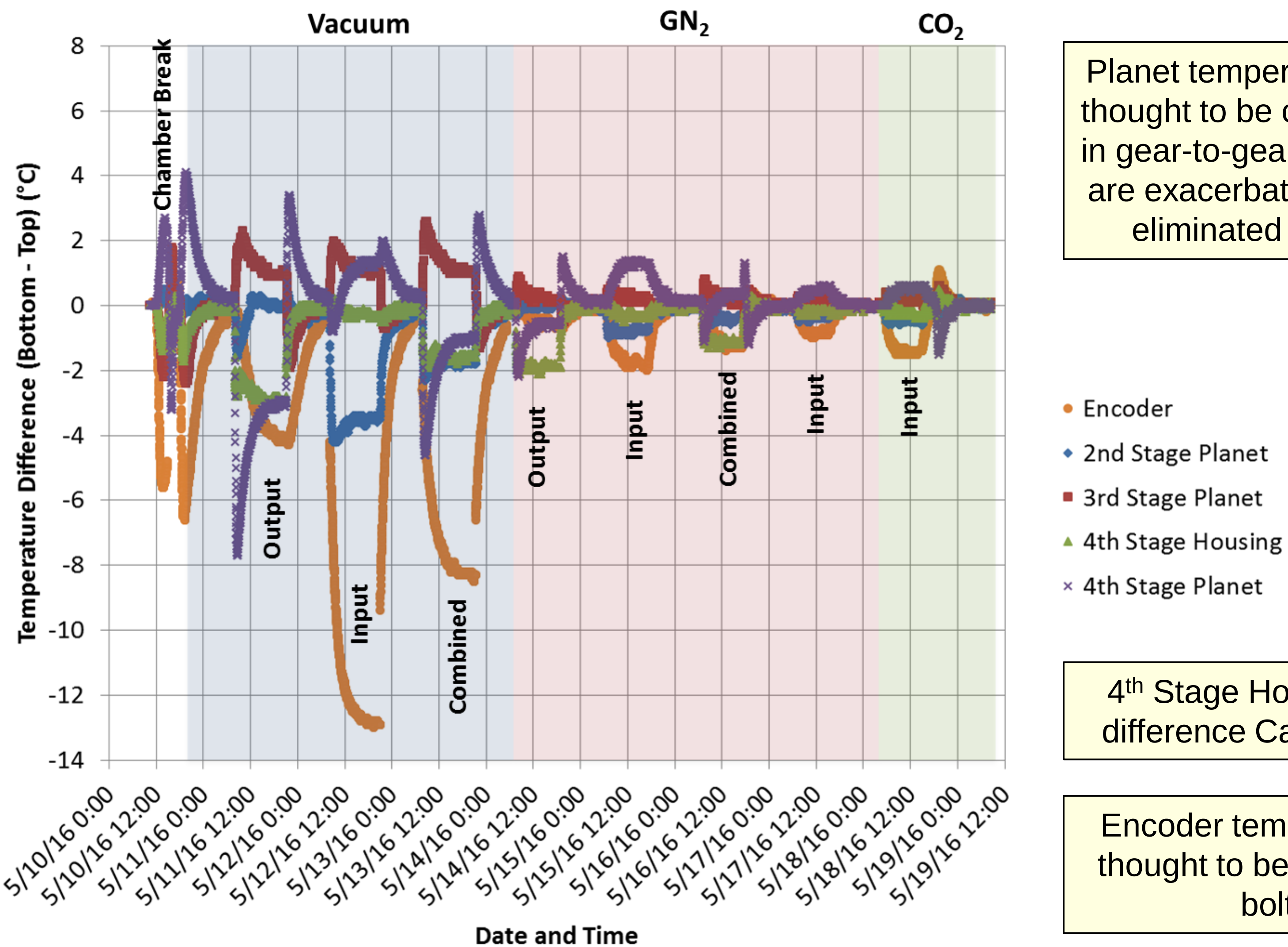

Planet temperature differences is thought to be caused by variations in gear-to-gear conductance. They are exacerbated in a vacuum and eliminated in GN_2 and CO_2.

4th Stage Housing temperature difference Caused by loose TC.

Encoder temperature difference thought to be caused by uneven bolt torques.

Gear Box Temperatures

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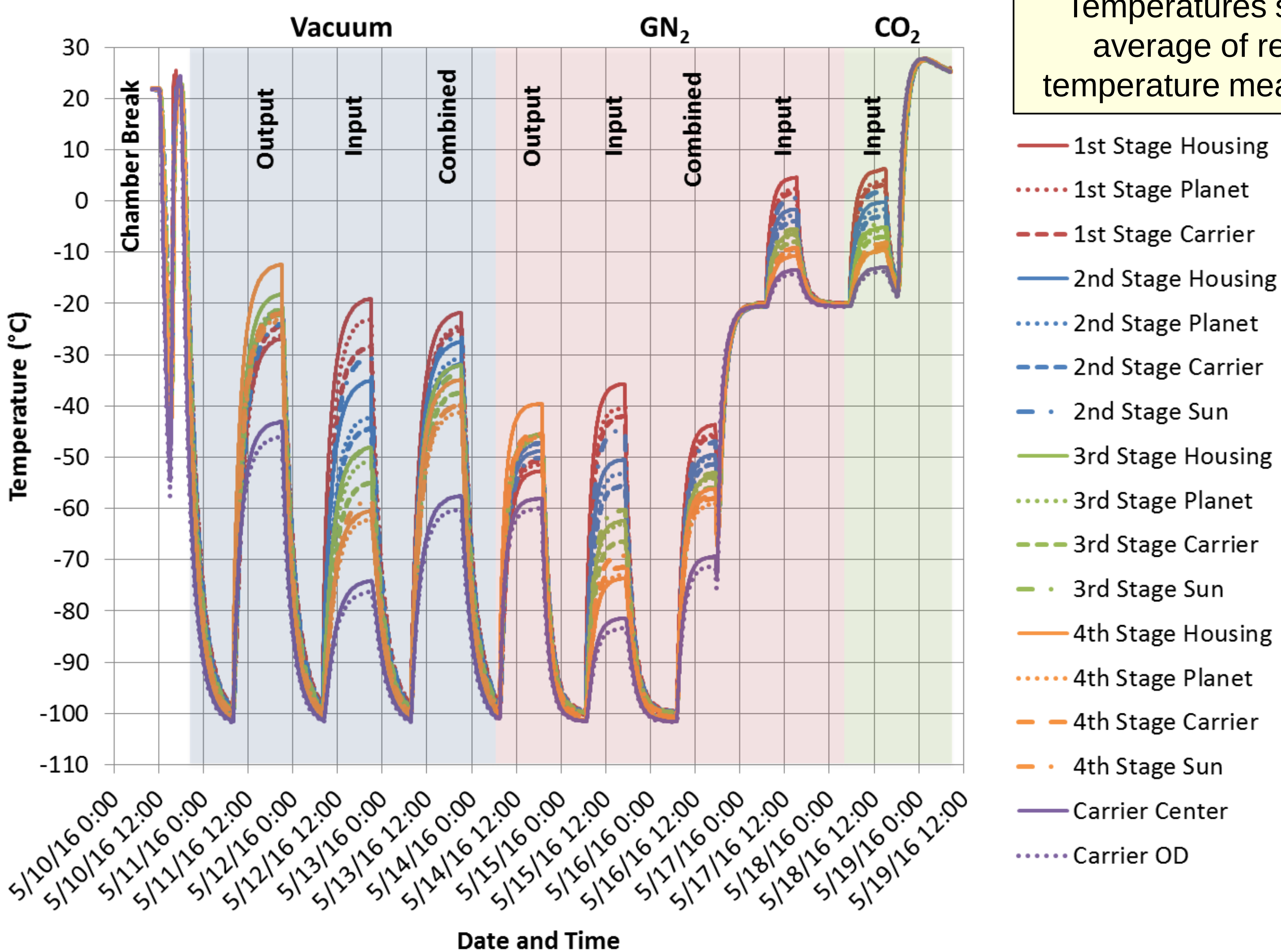
Temperatures shown use average of redundant temperature measurements.



Brake and Encoder Temperatures

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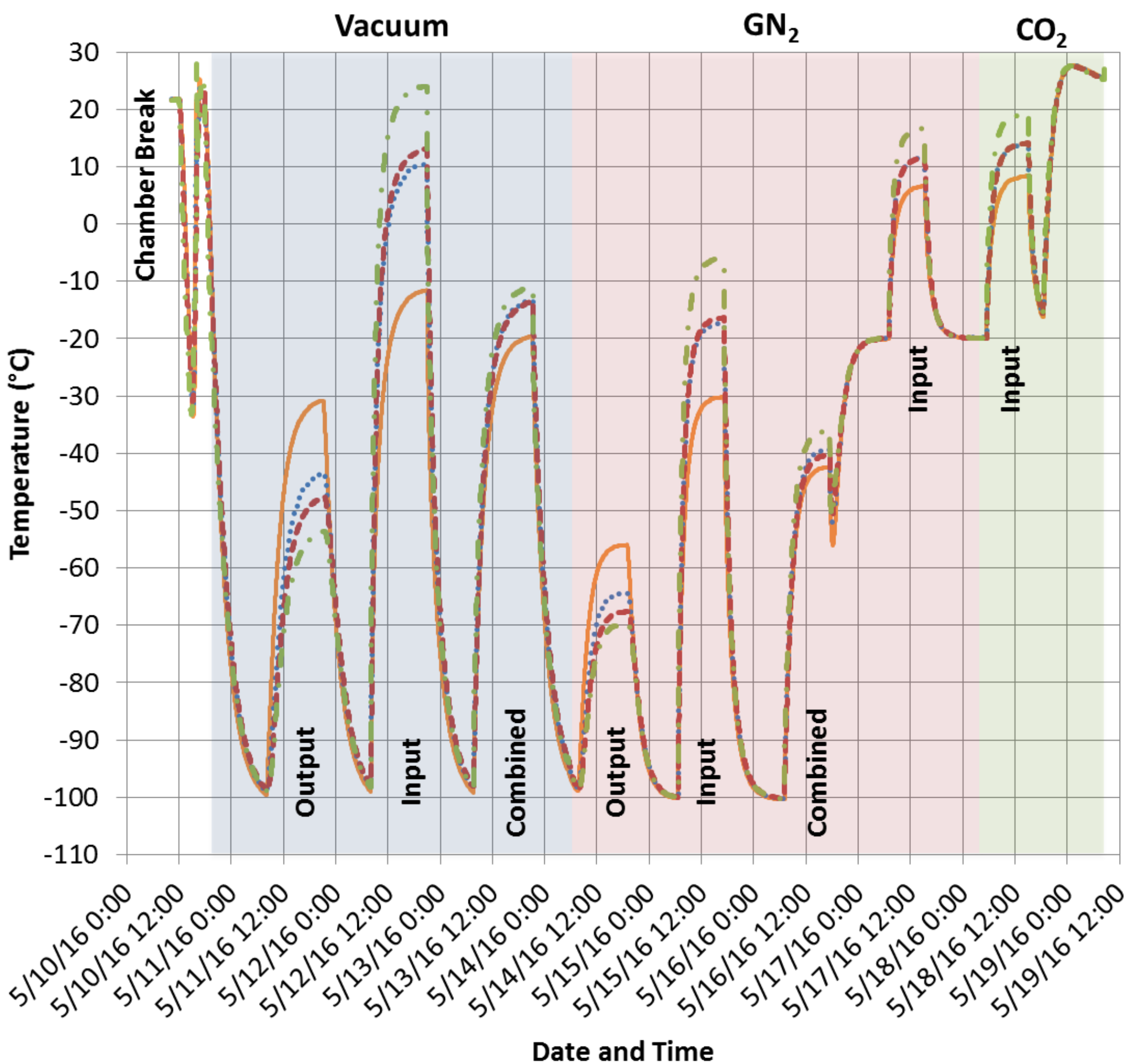

Temperatures shown use average of redundant temperature measurements.

Gearbox Maximum Gradients

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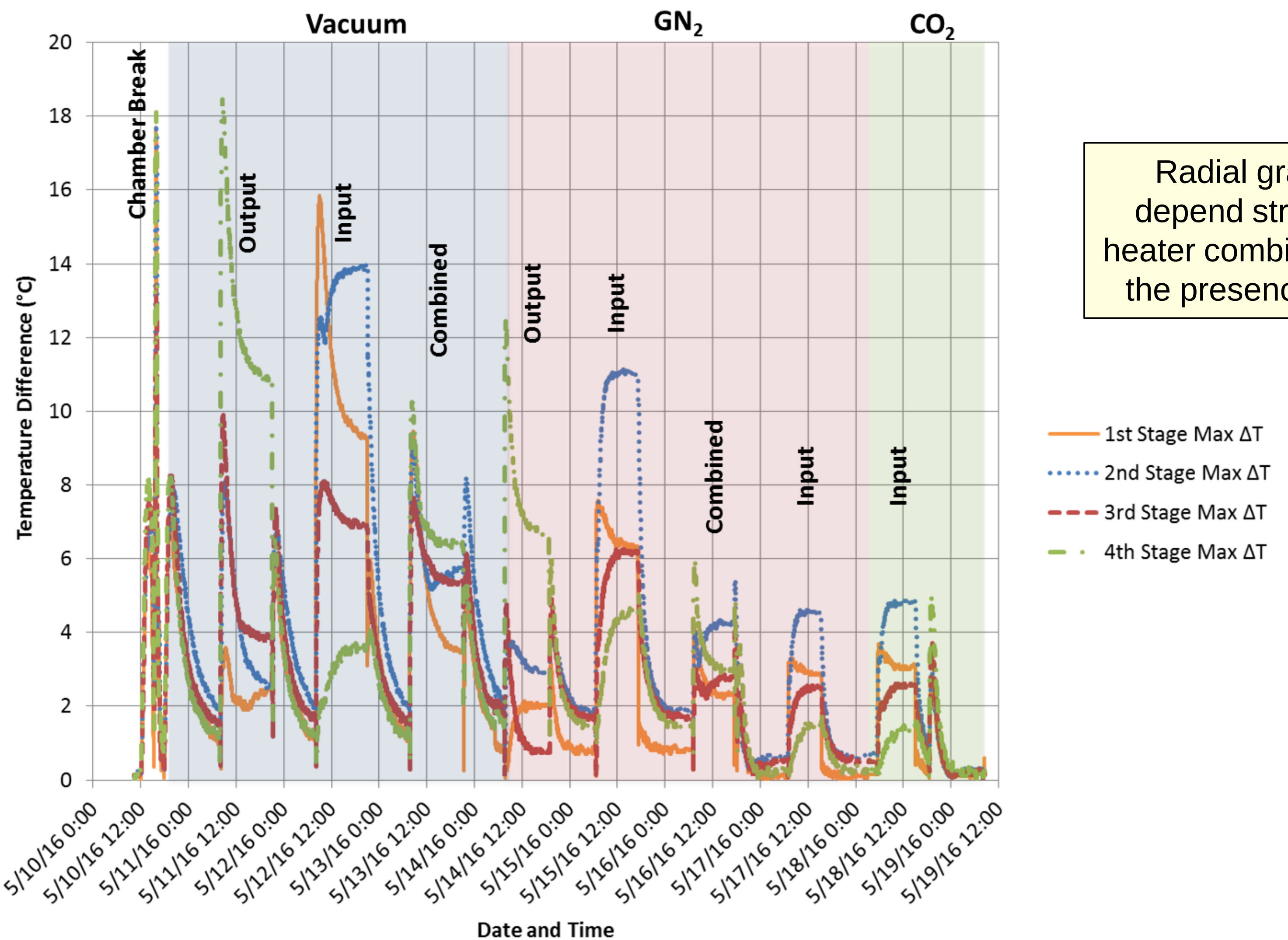

Radial gradients depend strongly on heater combination and the presence of gas.

Model Correlation

- Primary focus of model correlation was on bearing and gear-to-gear conductance in actuator gear box.
  - All actuator components were correlated and discussed in paper, but presentation will focus on these aspects.

- Correlation Principles:
  - Prioritize Gearbox Correlation
  - Maintain Physical Realism
  - Produce Generalizable Results
  - Maintain Model Conservatism

Use same multiplier for all bearing conductance values

Use same multiplier for all gear-to-gear conductance values

If correlated conductance values are uncertain, tend towards lower values

Bearing Conductance

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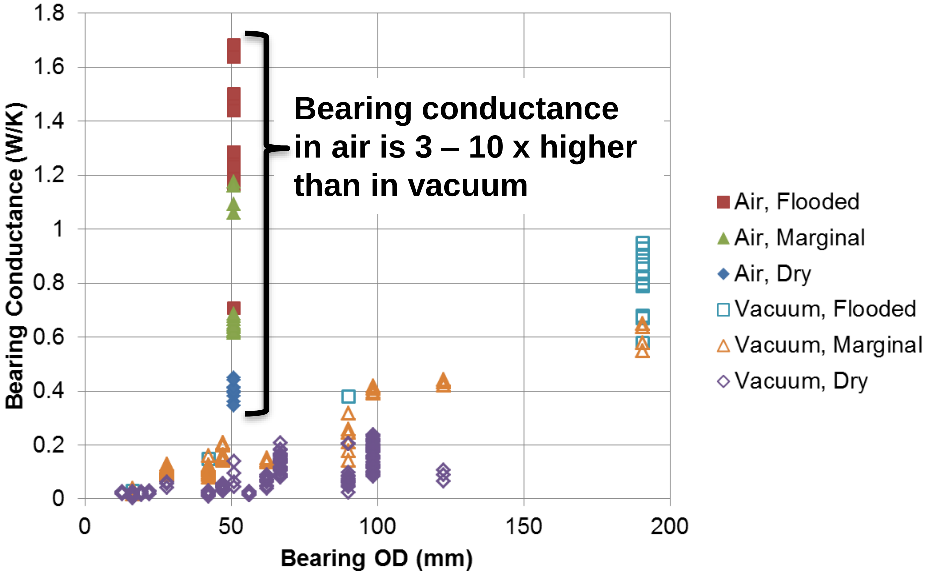
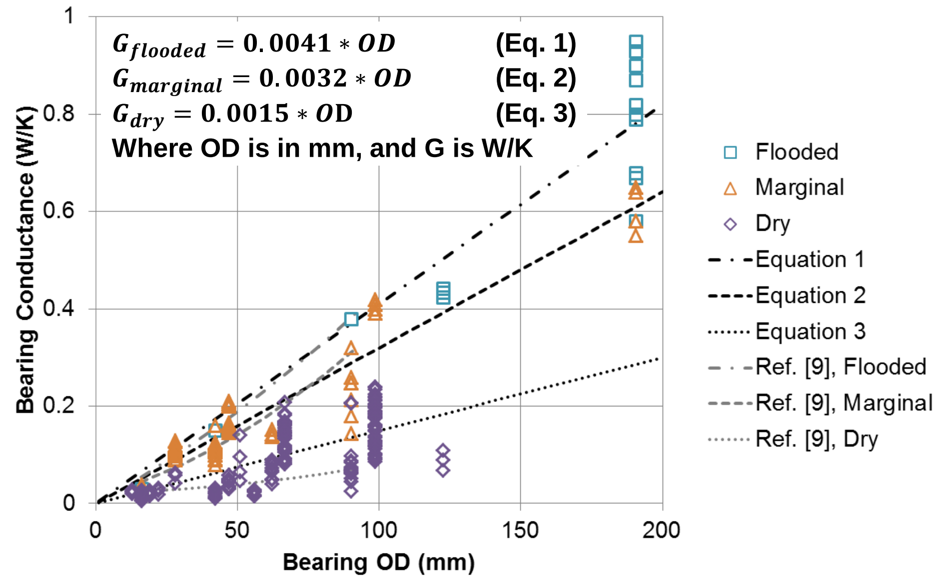
- Initial bearing conductance estimates were based off a literature review:
  - Bearing conductance is a function of bearing OD
  - Bearing conductance in is 3 – 10 x higher than in vacuum

- Model correlation confirmed use of 1x vacuum and 3x gas multipliers.



Bearing Conductance in Vacuum and Air



Vacuum Bearing Conductance Correlations

*Charts adapted from Redmond, M., Novak, K., and Mireles, V., "Static Ball Bearing Thermal Conductance in Air and Vacuum: Review and Correlation," *AIAA Journal of Thermophysics and Heat Transfer* (accepted).

Gear-to-Gear Contact Conductance

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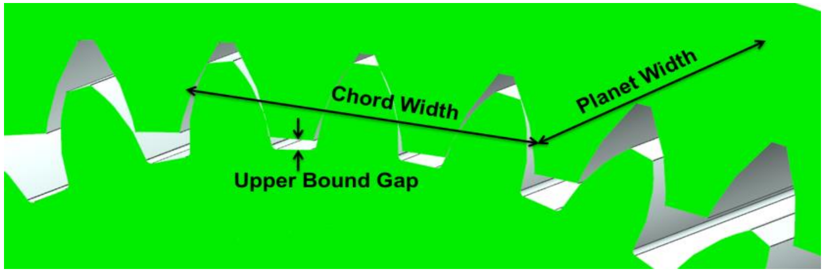
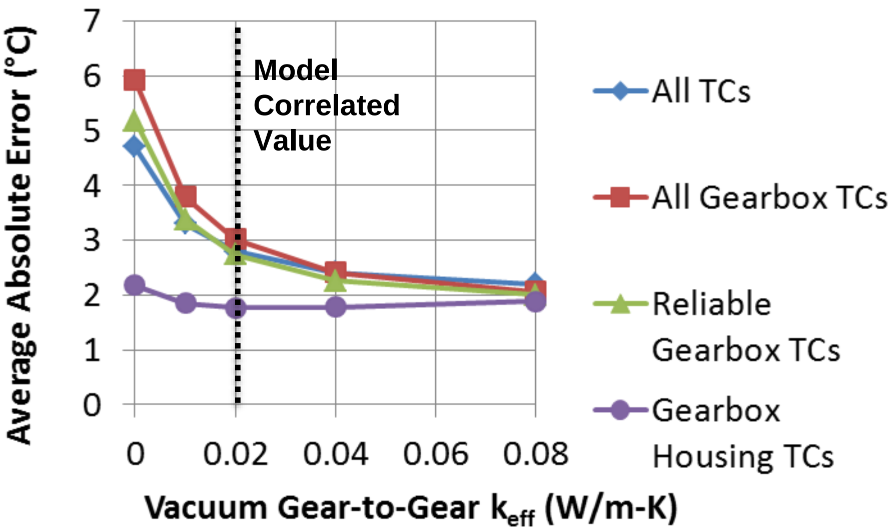
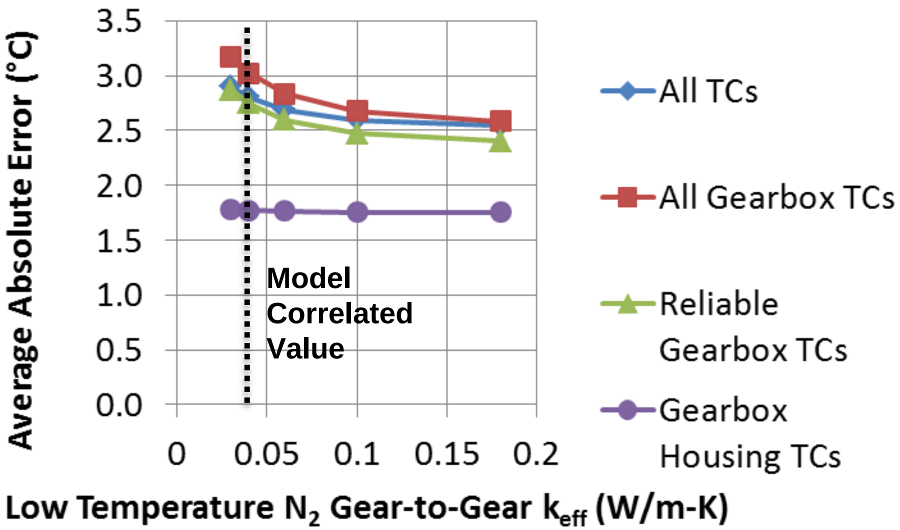
- Initial gear-to-gear conductance estimates were based off a measured A/L and assumed k_{eff}:
  - $k_{eff,vacuum}$ = 0 W/m-K
  - $k_{eff,gas}$ = 0.015 to 0.025 (gas)



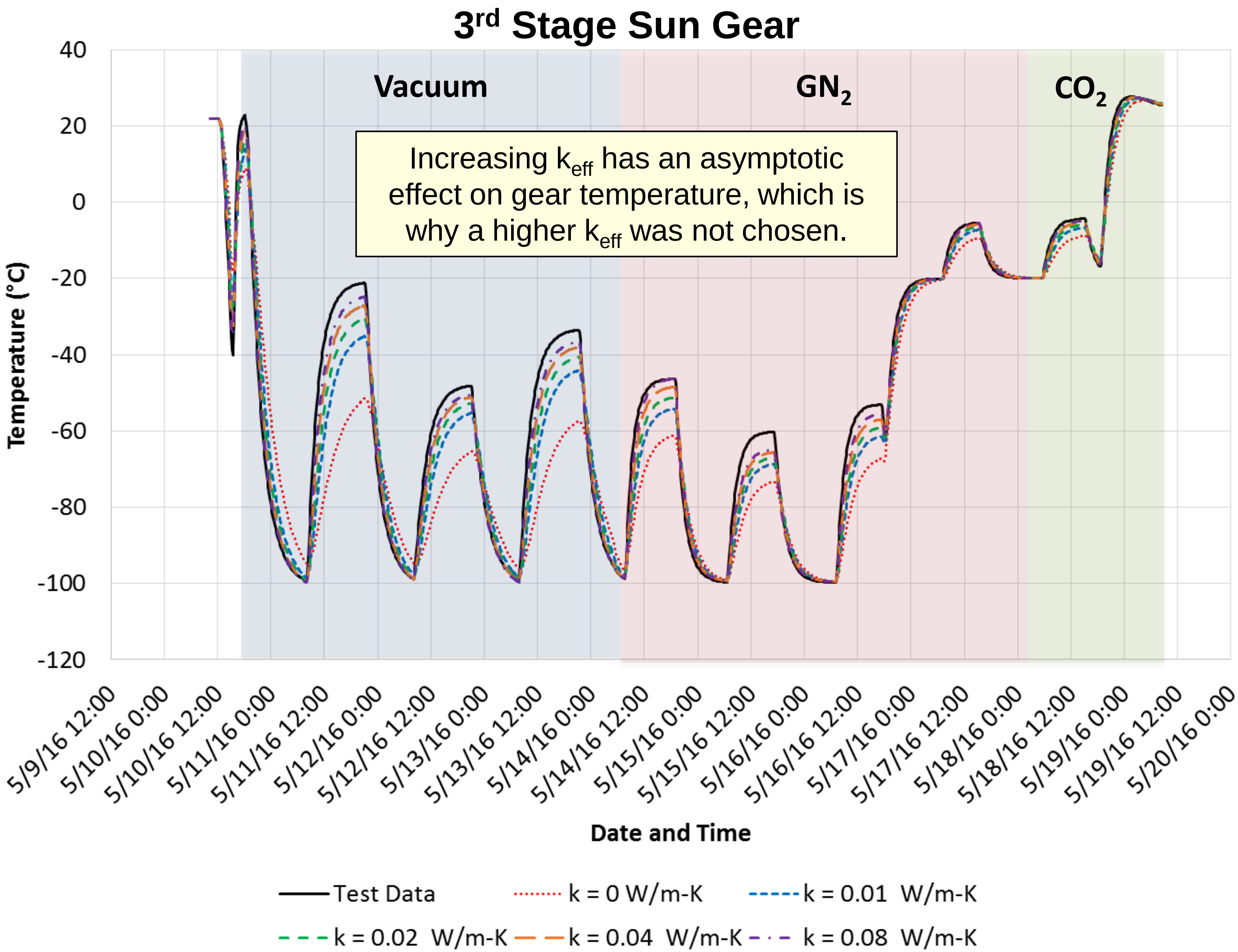
Method used to estimate gear-to-gear A/L

- Correlation indicates significantly increased conductance:
  - $k_{eff,vacuum}$ = 0.02 W/m-K (grease)
  - $k_{eff,gas}$ = 0.035 to 0.045 (grease + gas)





Gear-to-Gear Sensitivity



Model Improvement from Correlation

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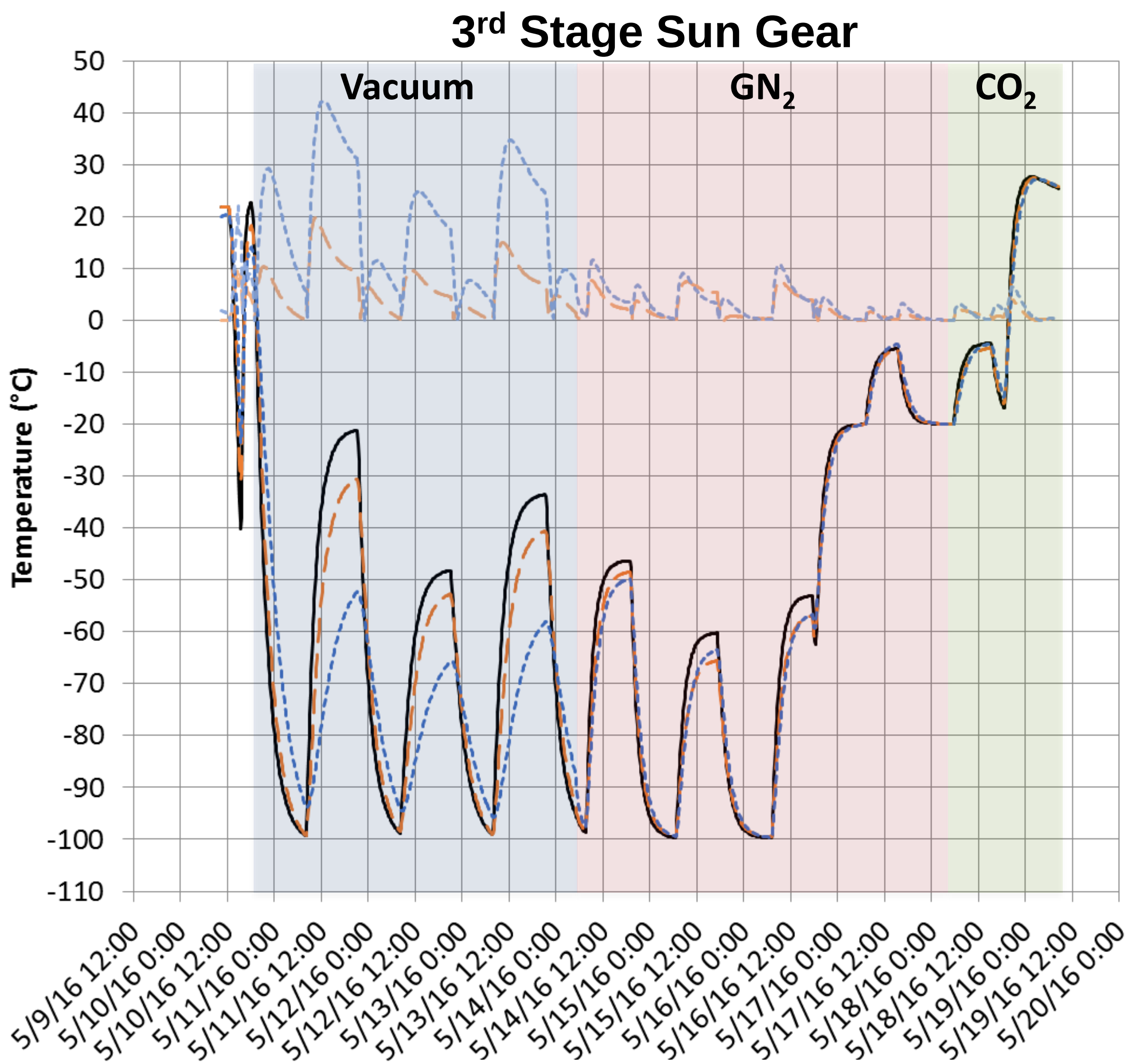

Model correlation significantly improved thermal model.

Lessons Learned

- Instrumenting a planetary gearbox with TCs required careful planning, practice bonding TCs, and small 36 gage TCs.
- Careful attention should be given to GSE and fit checks. Nearly all the oversights and challenges on this test were related to GSE.
- Bolted joints should always be torqued to a specified value.
- Having TCs on the chamber shroud and heat exchanger inlet nitrogen cooling lines is useful, especially if CO_2 testing is planned.
- Epoxy bonding bolted interfaces that need to be disassembled again should be avoided.

Conclusion

- This test was a success and all test objectives were met.
  - The average absolute error of all test data for the duration of the test was improved from 5.77 °C to 2.80 °C as a result of this model correlation.
- To our knowledge, this is the first time a planetary gear box has been internally instrumented and subjected to vacuum and low pressure thermal testing.
- Gravity effects on internal conductance values seems insignificant.
- Test results corroborate previously proposed vacuum bearing conductance values, and suggest using a multiplication factor of 3 for low pressure environments.
- Gear-to-gear conductance is present in both vacuum and low pressure environments, and can be estimated using the gear teeth geometry coupled with a thermal conductivity assumption.

Acknowledgements

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